Planar Systems, Inc. (American Display Consortium)

Patterning Technology for Color Flat-Panel Displays

In 1992, monochrome flat-panel displays (FPDs) for viewing essential data were becoming a key product differentiator for most electronics products, such as mobile phones and navigational devices. Analysts believed that color FPDs were the next advancement and would be a vital component of electronics products in the next decade. The worldwide market was forecasted to grow from $3.5 billion in 1992 to $14 billion in 1999. Color displays demanded much higher resolution than existing monochrome panels, and higher resolution required new methods for applying electrical conductors in minute, intricate patterns on glass plates. Grid patterns that had been greater than 100 micrometers on monochrome displays had to shrink to 2 to 50 micrometers (a micrometer is 1/1000 of a millimeter).

The American Display Consortium (ADC) formed in 1992 to explore enhancements to color FPD technology. The leading members were five small U.S. FPD manufacturers: Planar Systems, Inc., Plasmaco, Electro-Plasma, Inc., Photonics Imaging (now Photonics Systems, Inc.), and Tektronix, Inc. (an instrumentation company interested in flat panel technology). This group agreed to focus on developing mutually beneficial micropatterning technology (minute, intricate patterns for the electronic circuits) to support color FPDs. Because none of the companies were large enough to fund this research independently, they applied to the Advanced Technology Program (ATP) in early 1993. They believed their pre-competitive research would stimulate U.S. competition in a Japanese-dominated market.

Through their ATP-funded project, which began in 1994, the consortium made advances in micropatterning circuits, achieving a resolution down to 5 micrometers. Moreover, they increased panel size to meet consumer demand (up to 24 x 24 inches) and ultimately commercialized large, color FPDs. By the end of the three-year collaborative research project, the remaining active companies were Planar Systems, Kent Digital Science (now Kent Displays), Three-Five Systems, Inc., and FED Corp. (now eMagin Corp.). These FPD manufacturers continue to supply niche markets in the electronics industry (for example, avionics, medical, and global positioning system displays). Spillover applications of this research include computer chips, high-end printers, calibration plates, and x-ray systems. In 2003, U.S. manufacturers accounted for less than 1 percent of the $50 billion worldwide FPD market.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
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Research and data for Status Report 93-01-0054 were collected during January - March 2004.

Flat-Panel Displays Require Multiple Layers of Electro-Optical Material

Many flat-panel displays (FPDs) consist of layers of glass substrates with minute, complex-patterned electro-optical material between the layers in order to light up pixels to create images. Rows and columns of electrical conductors form an intricate grid pattern. FPDs consist of four basic types: liquid crystal displays (LCDs), electroluminescent (EL), plasma, and field emitter displays (FEDs).

By 1994, U.S. FPD manufacturers had developed adequate processes for making monochrome displays. The electrodes typically had dimensions greater than 100 micrometers (a micrometer is 1/1000 of a millimeter). However, as FPD technology was moving toward color, the requirement for patterning resolution increased significantly to 2 to 50 micrometers. Detailed color images required much finer patterning of the electrical conductors on the multilayered grid patterns, called wafers. Wafers could have up to 16 layers of metal, semiconductors, and dialectrics (nonconductors) to make the patterns. However, existing methods for applying the conductive material were inadequate. Furthermore, visual inspection methods being used at the time could not adequately characterize the color issues of chromaticity (quality), brightness, and gray scale (definition).

American Display Consortium Applies to ATP for Research Funding

The American Display Consortium (ADC), formed in 1992, was a group of U.S. FPD manufacturers focused on making patterning technology advances that would benefit all the members. The consortium initially included Planar Systems, Inc., Plasmaco (now part of Matsushita), Electro-Plasma, Inc. (now EPI), Tektronix, Inc., and Photonics Imaging (now Photonics Systems, Inc.). Their common FPD needs included in-process inspection and repair tools and high-density interconnects (chip on glass and silicon on glass). Individually, the companies were too small to pursue this fundamental micropatterning technology research. Therefore, in 1993, the consortium submitted a proposal to ATP to pursue a group of projects that would address the generic technology and infrastructure requirements for the patterning of color FPDs. Beginning in 1994, the projects initially included the following seven areas of research:

- Large-area photo-exposure tools
- Large-area photo masks
- Wet-etching tools
- Dry-etching tools
- Printing tools
- Panel alignment methods
- Final inspection tool

Changes within companies as well as lessons learned from these seven areas of research led to changes in research efforts. This included the addition of the following three new research areas:

- Patterning process for dielectric barrier layers
- Laser lithography endpoint monitors
- Low-cost color filter processes

ADC planned to expand membership to include suppliers to the flat-panel industry as well as manufacturers. It proposed to provide quarterly meetings, internal publishing, technical reports, and on-site visits to facilitate knowledge sharing, collaboration, consensus building, and technology transfer among all formal and informal members of the consortium (some members did not actively participate in the ATP-funded research and development).

FPD Advancement Could Benefit the U.S. Electronics Industry

ATP granted funding to the ADC in part because industry analysts had identified FPDs as a strategic technology for the growing U.S. electronics industry. While Japan already enjoyed a manufacturing lead, it was critical for the United States to regain market share. Semiconductors were a key component of the electronics products, receiving research and investments from the public and private sectors in the 1980s. Similarly, it was believed that FPDs would be a vital component of the electronics products in the 1990s, and that the display would become the key product differentiator for most electronic products (for example, personal digital assistants, cell phones, and computers). The worldwide market for FPDs was expected to grow from $3.5 billion in 1992 to $14 billion in 1999. Some of the process technology developed for FPDs would likely also apply to the semiconductor industry and the electro-optics industry (for example, image digitizers, copiers, sensors, scanners, hybrids, and multichip modules).

Consortium Develops Foundational, Pre-Competitive Research Steps

During the ATP-funded project, the ADC ultimately researched 10 supporting technologies that could advance U.S. competitiveness in the FPD industry. At its peak in terms of membership, the ADC included 13 U.S. FPD manufacturers: Planar Systems, Photonics Imaging, Optical Imaging Systems (OIS), Electro

Plasma, Inc., Norden Systems, Plasmaco, Standish Industries, Inc., Kent Displays, Inc., Silicon Video Corp., Three-Five Systems, Inc., AT&T Xerox, Coloray Display Corp., and Tektronix. Some actively collaborated and conducted research, while others only participated in quarterly meetings to gain knowledge. While Planar led the project, joint venture members divided up the tasks, relying heavily on six subcontractors: Microphase, Solid State Equipment Co. (SSEC), Plasma-Therm, Inc. (now part of Oerlikon-Buehrle), Photronics (now Infinite Graphics, Inc.), Tamarack Scientific, and YieldUp International (now FSI International). A summary of their ATP-funded research efforts in all 10 areas and their results upon the conclusion of the project follow:

1. **Photo Exposure Tools:** Photonics Imaging worked with a subcontractor, Pacific Infrared, to design contact printing exposure equipment intended to produce large-area printed circuit boards with resolutions down to 4 micrometers over a 40- x 40-inch area (phase 1) and then over a 60- x 60-inch area phase 2), while offering high yields of printed circuit boards.
   Results: This portion of the project was terminated in 1997. Approximately 70 percent of the effort was complete, but the final milestones could not be met because Photonics Imaging was unable to continue funding the effort. While the prototype did not lead to a commercially viable piece of equipment for manufacturing, the project participants advanced their knowledge in the areas of registration, scanning, and uniformity of exposure and tool size aspects.

2. **Large-Area Photo Masks:** This work was started by Tektronix and later was transferred to Planar (Tektronix shifted its business focus away from FPDs). Researchers intended to directly pattern chrome on glass, using a photo mask in sizes larger than 6 x 9 inches. Researchers intended to develop the tool set needed to establish the full mask processing capability (such as cleaning, developing, and etching) for these large-area chrome masks with resolution down to 5 micrometers. The integrity of the photomaster is a key factor in determining process yield and quality of the intricate patterns. Damage to the pattern or contamination on the photo tool were serious problems in the high-resolution, large-area artwork used in making FPDs.
   Results: Photronics, a subcontractor, achieved speed goals and improved dimension uniformity by 400 percent. Although not an original design goal, the new photo masks reduced chemical use by 70 percent, a significant environmental benefit. Tamarack Scientific, a subcontractor, scaled up its existing exposure equipment to expose the substrates through Photronics' masks (up to 840 x 1025 mm). Researchers optimized processes for individual glass vendors and effectively collected and analyzed data as an ongoing process.

3. **Wet-Etching Tools:** Researchers at Kent Digital Science (now Kent Displays) and Planar planned to develop wet-etching production tools and processes to produce reflective Cholesteric LCDs and EL displays with plastic substrates. Wet etching is the most widely used technique to define the substrate structures, the electrode patterns, and the color sub-pixels of FPDs. While the etcher would be intended for glass etching, the tools could be applied to other etching processes used in the manufacture of FPDs, such as the etching of indium tin oxide (ITO, a transparent plastic that conducts electricity), electrode metals, or other materials.
   Results, Wet-Etching Process: Kent researched plastic materials such as acrylic, polycarbonate, and polyester. Acrylic and polycarbonate's strengths were that they absorb ultraviolet radiation (protecting the liquid crystal) and were rigid substrates (requiring no special handling techniques). However, they were brittle and slightly bowed, making registration difficult. Polyester's strength was that it was easy to shape to final dimensions; however, it was flexible and required special tooling, and its air bubbles interfered with quality.
   Results, Wet-Etching Tool: Planar identified and designed cost-effective automated tools that addressed the critical handling steps in its immersion process line. Planar relied on two subcontractors: SSEC to design the faster automated system and YieldUp International to dry the glass substrates after wet etching. Operators no longer directly touched the glass. The new system provided a throughput of one substrate per minute. SSEC developed a method to load plates up to 500 x 550 mm into a chamber and spray the chemicals instead of immersing them. YieldUp received 10 patents for its automated processing technologies.

4. **Dry-Etching Tools:** Dry etching is expensive compared to wet etching. It is used for high resolution or deep etchings in the substrate. Dry etching is also advantageous when patterning water-sensitive materials (such as color phosphors). This research used dry etching to define high-resolution patterns (5 micrometers or less), such as those found in active-matrix LCDs. Planar researchers intended to design a machine with at least a 100-percent improvement in the ratio of the capital cost to the throughput (process speed). Plasma-Therm, a subcontractor, had developed a unique square plasma process chamber concept, which maximized the useful area for processing rectangular FPD substrates.
   Results: The team developed and implemented a dry-etch tool. Etchers were installed and were operational at Planar on 6-inch wafers. The team developed, characterized, and implemented an ITO etch process in a pilot run of high-resolution, active-matrix displays.

5. **Printing Tools:** Existing screen printing tools were limited to resolutions of 100 micrometers, and most equipment was designed for relatively small substrates. Plasmaco intended to develop printing equipment with advanced resolution capabilities of 50 micrometers for large-area substrates (20 x 20 inches).
   Results: Plasmaco evaluated the process and implemented a pilot for screen-printing evaluation. Initial screen-printing results far exceeded expectations. However, Plasmaco was purchased by Japanese manufacturer, Matsushita, in early 1996, and this research was discontinued.

6. **Panel Alignment Methods:** Color FPD production requires precise registration of multiple micropatterned images from one film layer, or substrate, to the next. This is difficult, because subsequent processing steps, such as heating and cooling, distort substrates. Electro Plasma focused on developing methods to compensate for substrate distortions, so that precise layer-to-layer registrations could be obtained on the order of 0.025 mm. Researchers intended to create unique per-plate masks on auxiliary plates, which are keys from the electrode patterns already processed into the glass, because it was doubtful that all distortions could be eliminated. They intended to adapt to process-induced distortions.
   Results: Electro Plasma attempted to align panels using a phosphor deposition process and found that high-resolution alignment was not practical. An electrophoretic method (using current to move phosphor particles) provided potential for high-volume manufacturing and for achieving a superior image. However, additional research was needed.

7. **Final Inspection Tool:** The prevailing practice for final testing relied on operators who made a visual inspection and took measurements. Planar Systems intended to provide an automated, objective inspection tool to test and evaluate the color flat-panel performance and to provide feedback for process improvement. Manufacturers needed to characterize the chromacity (quality and purity of color), brightness, and gray scale performance of full-color panels. Besides measuring the optical performance, the inspection tool needed to detect any defective pixels and then accept or reject the panel. The throughput goal was to characterize 50 to 100 video-graphics-array (VGA)-sized panels per day. Final inspection meant developing nondestructive testing and evaluation techniques for the quality inspection process.
   Results: Initial results were positive and appeared to apply to all emissive displays. Subcontractor Photronics found a solution that solved the alignment problem for 30-inch plasma color displays by using an etching groove structure. The company achieved minimum specifications for metrology and defect detection, which they verified on VGA-color displays. They implemented automated device handling and test-data logging for a miniature display product. They successfully measured chromacity, image retention and flicker, and automated substrate handling for miniature displays.

Three research areas were added over the course of the project:

8. **Patterning Process for Dielectric Barrier Layers:** Three-Five Systems researched producing micropatterns on dielectric layers of silicon dioxide.
   Results: Researchers found that film hardness varies in different materials. They produced a uniform film over 14- x 16-inch substrates. They were continuing research upon conclusion of the ATP-funded project.

9. **Laser Lithography Endpoint Monitors:** FED Corp. (now eMagin Corp.) researchers intended to develop and characterize a technique to develop in-process photoresist laser endpoints (putting down a pattern where the circuits would not be applied) for FED applications. The goals were to achieve lithography performance improvement with low voltage, low cost, and increased volume. Micropatterns should have resolutions down to 0.1 micrometers, with tight tolerance and real-time process control.
   Results: Actual display substrates gave reasonable signals to be able to determine a reference point. Endpoint detection is feasible for manufacturing FEDs patterned by laser interference lithography. Research was ongoing at the end of this project.

10. **Low-Cost Color Filter Processes:** Standish Industries researchers studied the color filter process. They examined screen printing approaches (direct print images, print blocks, and photolithographical pattern images), as well as changing materials from photoresists to inks.
    Results: Standish established materials for the first evaluation, where chromacity was close to requirements, thickness was acceptable, and resolution was achieved. They procured equipment, to include a printer, an emulsion coater, and a screen expose unit, and established a prototype low-cost color filter process. Further testing was needed to demonstrate repeatability.

The ADC membership changed during the project. Tektronix left the group in 1995, when it stopped pursuing FPD manufacturing. Plasmaco left after it was purchased by Matsushita in 1996. Upon conclusion of the project in 1997, the remaining four active consortium members were Planar Systems, Kent Displays, Standish Industries, and Three-Five Systems.

ATP Research Yields Mixed Results

While the project made reasonable technical advances, the ATP-funded FPD research yielded mixed results. In late 1997, Planar Systems and Three-Five Systems were doing well. Both had successfully broadened the number and scope of their niches, such as high-resolution medical displays. The EL work of Planar and the LCD work of Standish Industries and Three-Five Systems appeared to be the most synergistic and to have the most significant market opportunities for these firms.

Color FPD production requires precise registration of multiple micropatterned images from one film layer to the next.

Photronics (now Infinite Graphics, Inc. or IGI) successfully commercialized large-area photo masks using Tamarack Scientific's scanning and exposure tools. They had processed 280 large-area plates using the process developed during this ATP-funded project (at $2,000 per plate as of September 1997). Three-Five Systems was using Photronics' photo mask process, which allowed them to use a U.S. rather than a foreign manufacturer. Planar Systems scheduled the mask cleaner for production in their new EL expansion line, anticipated in 1998, and increased productivity by 60 percent. Photronics was becoming an important supplier to the semiconductor industry, as well as to the FPD industry (which was only 5 percent of Photronics' total sales). Their enhancement laser pattern generator wrote high-resolution patterns on glass substrates up to 24 x 24 inches.

SSEC used the wet-etching work developed during this project to support both FPD and semiconductor manufacturers. This project provided one of SSEC's first orders for spraying wet-etching chemicals and enabled the company to refine its technology. SSEC successfully commercialized its spray wet-etching machines.

Standish Industries further developed color filtering, but was unable to build color displays with high enough yields to enter commercial production. Standish was purchased by Planar in 1998. SSEC, Tamarack Scientific, and YieldUp International were expected to have marketing opportunities elsewhere as well as for ongoing FPD development and manufacturing.

After project conclusion, Kent Displays continued research into wet-etching processes on plastic substrates and developed large plastic prototypes by 1998. Planar also continued developing wet-etching tools.

Other company achievements resulting from this ATP-funded project included the following:

- Plasma-Therm successfully commercialized dry-etching processes in its Clusterlock 7000 on 6-inch wafers. Planar used the Plasma-Therm etcher to produce active-matrix EL microdisplays.
- After project conclusion, the FED Corporation received significant additional funding from investors and government agencies in order to further develop high-definition field emission display technology.
- Three-Five Systems continued developing dielectric barrier layers.

U.S. FPD Manufacturing Shrinks in 1999

Asian competition hit U.S. FPD manufacturing hard in 1999. The production capacity in China for monochrome small LCDs increased significantly. High-performance active matrix LCDs were becoming a commodity item, leading to lower prices, in much the same way as the dynamic random-access memory (DRAM) chip and the bare silicon wafer had become commodity items in the computer industry. Retail prices dropped for electronics such as laptop computers. When global demand temporarily shrank, Asian suppliers were prepared to reduce prices lower than the cost of production in the United States. The cost to develop and manufacture color FPDs was too high to compete, and, as a result, U.S. firms increased their FPD outsourcing from Asian manufacturers. OIS went out of business, and Plasma-Therm was sold to a Swiss company, Oerlikon-Buehrle. Three-Five Systems was able to outsource dielectric barrier layers for less and discontinued its ATP-funded research.

Kent Displays found that using wet etching during manufacturing was too expensive and discontinued its use. As of 2004, they still produced FPDs using glass and have moved on to using conducting polymer substrates, where circuits are printed rather than etched. The Planar EL manufacturing plant, which opened in 2000 but closed in 2003, used several of the processes developed during this project.

Planar continued developing its final inspection tool and used it for miniature display products based on EL. The company was not able to develop a high-volume business for these products, and the program was shut down in 2002.

The worldwide market for FPDs was expected to grow from $3.5 billion in 1992 to $14 billion in 1999.

FED continued developing its laser lithography endpoint monitor. Ultimately, the company gave up FPD production and in 1999 changed its technology focus to active matrix organic light-emitting diode (OLED) microdisplay technology. The company changed its name to eMagin in 2000.

The future of U.S. FPD manufacturing is uncertain. Only four ADC niche players remain in the business: Planar Systems, Three-Five Systems, Kent Displays, and eMagin. They provide specialty applications, such as medical instrument displays, “ruggedized” military displays, automated teller machines and outdoor kiosks, and navigation instruments, such as for global positioning systems for trucking and avionics.[1]

Electronics Manufacturing Spillover Provides a Bright Spot

Some of the ATP-funded research has been commercialized through spillover electronics applications. The manufacturing processes for FPDs, such as micropatterning and producing multi-layered integrated circuit wafers, also apply to other high-resolution manufacturing.

IGI continues to lead the market, using its enhancement laser generator developed for large-area photo masks. Resolutions have increased from micrometers to nanometers (a nanometer is 1/1000 of a micrometer). By 2004, IGI was able to work on panels up to 32 x 28 inches. It continues to sell customized large-area masks for use in high-end printer circuits, calibration plates, and x-ray systems, as well as for use in FPDs account for 5 to 10 percent of their business, or $500,000 to $900,000 annually (based on $8.8 million in 2002

[1] Freedonia Group, *Electronic Displays,* March 2004.

sales). The global market for photo masks was expected to reach $3 billion in 2003 (up from $2.4 billion in 2001).[2]

SSEC still sells its wafer wet chemistry systems as of 2004, which represents approximately 10 to 15 percent of the company's business. Tamarack Scientific continues to sell large-area scanning and exposure tools, with resolution down to 3 micrometers.

YieldUp sold its patented wet-etch processing tools to several FPD manufacturers. These processes are key components of a larger system, which the company still uses for integrated circuits (on glass substrates) and computer chips (on silicon wafers) of up to 12-inch diameter (their primary business as of 2004). Other applications include hard disk drive cleaning and photo mask cleaning. The company had sales of $88.8 million in 2003. Wet-etching tools are a critical area in semiconductor manufacturing, which is also experiencing extreme pricing pressure. The wet-etch-clean market shrank 40 percent from 2002 to 2003 but is expected to grow again to $1.5 billion in 2005.

Conclusion

In 1994, at the time the ATP-funded color flat-panel display (FPD) research began, the technology was still in its infancy. U.S. manufacturers had competed effectively in the market with their monochrome displays and hoped to continue this success in the high-resolution color environment. Displays were recognized as a key differentiator in numerous electronic products, such as mobile phones and navigation instruments. Existing photo exposure equipment was no longer adequate for producing high-resolution circuit micropatterns for color FPDs, in which critical dimensions were as small as 2 to 50 micrometers (down from 100 micrometers) on panels as large as 24 x 24 inches (up from 6 x 9 inches). Thirteen U.S. manufacturers participated in the American Display Consortium from 1994 to 1997. The consortium members, relying substantially on subcontractors to develop the tools, achieved higher resolutions and larger dimensions by making improvements in technologies for etching, printing, alignment, and inspection. They shared knowledge and received 10 patents, but research into FPDs achieved mixed results. U.S. flat-panel manufacturers made a strong showing on the global market until 1999. At that time, price-competitive Asian manufacturers drove prices so low that U.S. manufacturers had to focus on niche markets, such as automated teller machines and outdoor kiosks, "ruggedized" military applications, microdisplays, and avionics and other navigation instruments. They captured less than one percent of the global $50 billion FPD market in 2003, but new innovations keep surfacing. U.S. manufacturers of high-resolution printers, x-ray systems, and computer chips have also benefited from the high-resolution tools developed during the ATP-funded research.

[2] *Solid State Technology,* August 2002.

PROJECT HIGHLIGHTS
Planar Systems, Inc. (American Display Consortium)

Project Title: Patterning Technology for Color Flat-Panel Displays (FPDs)

Project: To develop patterning technologies necessary to manufacture color FPDs, including large-area photo exposure tools, large-area masks, wet- and dry-etching tools, printing tools, panel alignment methods, and a final inspection tool.

Duration: 4/18/1994-10/17/1997
ATP Number: 93-01-0054

Funding (in thousands):

ATP Final Cost	$5,670	49%
Participant Final Cost	5,901	51%
Total	$11,571	

Accomplishments: With ATP funding, researchers made the following technology advancements, which benefit the FPD and semiconductor industries.

- Implemented methods to produce large-area photo masks up to 24 x 24 inches (up from 6 x 9 inches), increasing dimensional uniformity by 400 percent and reducing chemical use by 70 percent
- Implemented automated wet-etching processes and tools and achieved a throughput of one substrate per minute
- Implemented a dry-etching process for 6-inch wafers
- Implemented a final inspection process for miniature displays, measuring chromacity, image retention and flicker, and test data logging
- Developed a patterning process for dielectric barrier layers
- Determined that endpoint detection is feasible for laser interference lithography; pursued additional funding to continue research

Research and development into wet etching led to 10 key technology patents that aid in processing silicon wafers for multiple uses, including manufacturing FPDs and computing chips. These were awarded to subcontractor YieldUP International (now FSI International, Inc.).

- "Ultra-low particle semiconductor method" (No. 5,634,978: filed November 14, 1994; granted June 3, 1997)
- "Method for cleaning and drying a semiconductor wafer" (No. 5,571,337: filed May 9, 1995; granted November 5, 1996)
- "Ultra-low particle semiconductor cleaner" (No. 5,772,784: filed November 8, 1995; granted June 30, 1998)
- "Ultra-low particle semiconductor apparatus" (No. 5,685,327: filed August 8, 1996; granted November 11, 1997)
- "Method and apparatus for cleaning wafers using multiple tanks" (No. 5,849,104: filed September 19, 1996; granted December 15, 1998)
- "Ultra-low particle semiconductor cleaner" (No. 5,868,150: filed May 22, 1997; granted February 9, 1999)
- "Ultra-low particle semiconductor cleaner" (No. 5,878,760: filed May 22, 1997; granted March 9, 1999)
- "Ultra-low particle disk cleaner" (No. 5,873,947: filed August 6, 1997; granted February 23, 1999)
- "Ultra-low particle semiconductor cleaner" (No. 5,891,256: filed December 29, 1997; granted April 6, 1999)
- "Cleaning and drying photoresist coated wafers" (No. 5,932,027: filed January 12, 1998; granted August 3, 1999)

Commercialization Status: Research led to some near-term commercial successes, which did not last, as well as several long-term commercial successes.

- Subcontractor Plasma-Therm successfully commercialized dry-etching processes in its Clusterlock 7000 for 6-inch wafers. Planar used this etcher to produce active-matrix electroluminescent microdisplays until 2002. Plasma-Therm was sold to a Swiss company, Oerlikon-Buehrle, in 1999.

- Subcontractor Photronics (now Infinite Graphics, Inc.) provides commercialized customized large-area photo masks for use in high-end printer circuits, calibration plates, x-ray systems, and FPDs (this work accounts for 5 to 10 percent of their business). This technology relies on two processes that were developed during this ATP-funded project: mask cleaning and laser pattern generating.

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- Subcontractor YieldUp (now FSI) developed automated wet-etch processing tools. These are now used for FPDs, but primarily for computer chip manufacturing. They are also used in hard disk drive cleaning and photo mask cleaning. Currently, the company markets the following larger processing systems, for which the ATP-funded technology was key: ZETA Spray Cleaning System, ANTARES CX Advanced Cleaning System, EXCALIBUR Vapor HF Etching System, MERCURY Spray Cleaning System, YieldUP 4000 Immersion Etch System, YieldUP 2000 Rinse Dry Module, and YieldUP 2100 STG Rinse Dry Integration Module.

Outlook: The outlook for U.S. FPD manufacturing is poor, with U.S. manufacturers' share of this $50 billion global market at less than one percent in 2003. The foundational manufacturing technologies developed during this project apply to other electronics applications, primarily computer chip manufacturing. The large-area, high-resolution photo mask processes contribute to a $3 billion industry. The automated wet-etch tools were commercialized in wafer-processing machines, which improved throughput in semiconductor manufacturing. Wafer processing has also endured extreme pricing pressures, and the market shrank 40 percent in 2002.

Composite Performance Score: * *

Company:
Planar Systems, Inc.
1195 N.W. Compton Drive
Beaverton, OR 97006-1992

Contact: Chris King
Phone: (503) 748-1100

Company:
Kent Displays, Inc.
343 Portage Boulevard
Kent, OH 44240

Contact: Bill Doane
Phone: (330) 673-8784

Company:
Three-Five Systems, Inc.
1600 North Desert Drive
Tempe, AZ 85281-1230

Contact: Dr. Joe Morrissy
Phone: (602) 389-8600

Subcontractors:
FSI International, Inc. (formerly YieldUp)
Headquarters/Surface Conditioning Business
3455 Lyman Boulevard
Chaska, MN 55318-3052

Solid State Equipment Corp. (SSEC)
Suite 600
303 Almaden Boulevard
San Jose, CA 95110

Tamarack Scientific Co., Inc.
220 Klug Circle
Corona, CA 92880-5409

Infinite Graphics, Inc. (formerly Photronics)
815 N. Wooten Road
Colorado Springs, CO 80915

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